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6. AUTHOR(S)

W.C. Griffith
W.H. Hall
L.G. Lee   J.N. Perkins

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

North Carlina State University
School of Engineering, Engineering Design Center
Raleigh, NC 27650

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TRANSIENTS   IN

TURBOCOMPRESSORS

ENGINEERING

by
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W. C. Griffith, W. H. Hall, L. G. Lee, and

J. N. Perkins

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for a cooperative program between

United Technology Research Center

and

North Carolina State University

SCHOOL OF ENGINEERING

NORTH CAROLINA STATE UNIVERSITY

RALEIGH, NORTH CAROLINA

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I.   INTRODUCTION

Designers of axial flow jet engine compressors have achieved substantial

gains in both pressure rise per stage and in reducing irreversible losses through

years of analysis and development testing under nearly steady flow conditions.

Non-steady inlet flow conditions produced by a number of aircraft operations

have, however, continued to challenge the industry with problems of transient

flows for which basic understanding is largely absent. In particular the

phenomenon of transient rotating stall within individual compressor stages

remains an unsolved problem. Observations indicate that distorted inlet flows

generate transient instabilities that at least produce losses and may grow to

significant compressor stall. It is important to decrease sensitivity to the

effects of inlet distortion without reducing performance during steady operation.

Dual goals are, therefore, to design engines having reduced likelihood of

incurring transient stall and also the ability to rapidly clear any stall that

arises and then return to normal operation. ·

Transient distortions of inlet flow may be produced by aircraft maneuvers,

atmospheric gusts, take-off in a cross wind, and the firing of weapons. To the

compressor the transient may appear as a change in one or more component of the

inlet velocity vector, a change in gas temperature or pressure, or a variation in

gas composition and hence specific heat ratio.

For the present project a single element of inlet flow distortion was selected;

variation of the axial component of velocity. This choice reflected discussions

with a number of interested parties and was based on the availability of both an

appropriate experimental facility (Ref. 1) and some preliminary theoretical work

(Refs. 2-4). The specific form of axial flow distortion to be studied involved

a sinusoidal variation around the circumference of the inlet, generated by a wire

screen of varying Mesh sizes for which a design method was also available (Ref. 5).

Approximately a 20% amplitude change in axial velocity was desired, and screens giving both a one-per-revolution and multiple cycles per revolution would be used to determine any dependence of effects on the dimensionless frequency parameter $\frac{wx}{v}$ used in rotor and oscillating cascade work.

The experimental and theoretical effort conducted under this project was the result of a cooperative arrangement between North Carolina State University (NCSU) and the United Technologies Research Center (UTRC). UTRC provided access to their Large Scale Rotating Rig (LSRR-I and later a second version, LSRR-II), engineering supervision and technician support to NCSU graduate students who moved to East Hartford for the conduct of experiments. Other students, both undergraduates and graduates, worked as research assistants on the NCSU campus on theoretical aspects of the problem. The principal investigators and students are identified later in this report.

Subsequent sections deal respectively with the experimental and theoretical approach, exploratory tests with a one-cycle distortion screen, theoretical modelling using an actuator disk, thin blade modelling, and experiments using movable multi-cycle screens. Finally documentation on project participants, the relation to other programs, and reports issued are given.

Among the various possible distortion modes, a circumferential variation of inlet axial velocity has been observed to produce a large effect on compressor performance and stall line. Rotor blades are exposed to a non-steady flow field under such conditions even though the main flow is steady (neglecting stator wakes). During those parts of a revolution where blades are heavily loaded, their performance and stall characteristics are quite different from average steady state conditions.

It is useful to consider the possible flow fields using the diagram shown in Fig. 1. This shows four regimes of compressor operation: I) undistorted flow with no rotating stall present, II) distorted flow with no rotating stall present (note that this could still imply that some of the blades are operating transiently in a badly stalled condition), III) compressor operation in rotating stall with uniform conditions far upstream, i.e., no imposed inlet distortion, and IV) compressor operation in rotating stall with an imposed inlet distortion. The boundaries that separate regions I and III and II and IV, denoted as subregions I-III and II-IV are also significant.

The problem areas that have been discussed above can be seen to fall in regions II, III, IV and II-IV. However, of these regions, IV is perhaps the one in which interest is less pressing at the present time, for two reasons. The first is that even if a distortion is the stall-inducing event, the distortion is often removed subsequent to the onset of stall, as for example in armament firing, or inlet separation during maneuvers. In these situations, the conditions that caused the stall are short-term transients that decay rapidly, leaving the compressor in a stalled condition although the flow entering the inlet is uniform. The second reason is that the complexities of the flow in region IV are more severe than those in III and since the latter is still not well understood, it is

	Uniform Inlet Flow	Distorted Inlet Flow
Unstalled Operation	I	II
Transition	I/III	II/IV
Rotating Stall	III	IV

Fig. 1   Flow Regimes for Compressor Operation.
Regions II and II/IV were of principal interest
in this investigation, but some observations were
made in each region.

advisable to attempt to solve the (supposedly) simpler problem first before attempting to deal with the combined phenomena. Therefore, either compressor operation in rotating stall, with no imposed inlet distortion, or compressor operation with inlet distortion in a flow range up to and including the inception of rotating stall (regions II, III, and II-IV) could be investigated. However of these remaining regions, it is region II (and II-IV) to which the capabilities of the present experimental apparatus, as well as the analytical methods that are being developed, are most readily applicable.

To gain insight into general rotor performance in non-stationary flows as well as the processes leading to transient blade stall, measurements would be needed in both the laboratory and rotating frames of reference. Stationary frame static and total pressures would be needed at both upstream and down-stream locations and at several circumferential locations to map flow distortion by the screens. In the preliminary runs instrumentation was installed at eight evenly-spaced circumferential locations, all at midspan. For the later runs a new mechanism was built for moving the screen holder so that every element of the distorted flow could be brought past any given stationary probe. Also, five radial locations were chosen to determine the extent of induced radial velocities.

In the rotating frame, pneumatic pressure taps, miniature pressure trans-ducers, and hot-film gages would provide data on conditions at the blade surface, while a combined total pressure - triaxial hot wire probe would give data on the blade wake. This probe could be traversed radially as well as circumferentially across blade wakes.

The instrumentation plan just outlined was developed in parallel to both guide the analysis and interpretation of experimental results and to provide a predictive model of transient flows through rotors. Two modelling approaches were employed, both computer-based. One employs the concept of an actuator disk in

which the flow through the rotor is replaced by an instantaneous change in
local flow properties, the other applies thin airfoil theory. Both models
are two-dimensional, time dependent approximations.

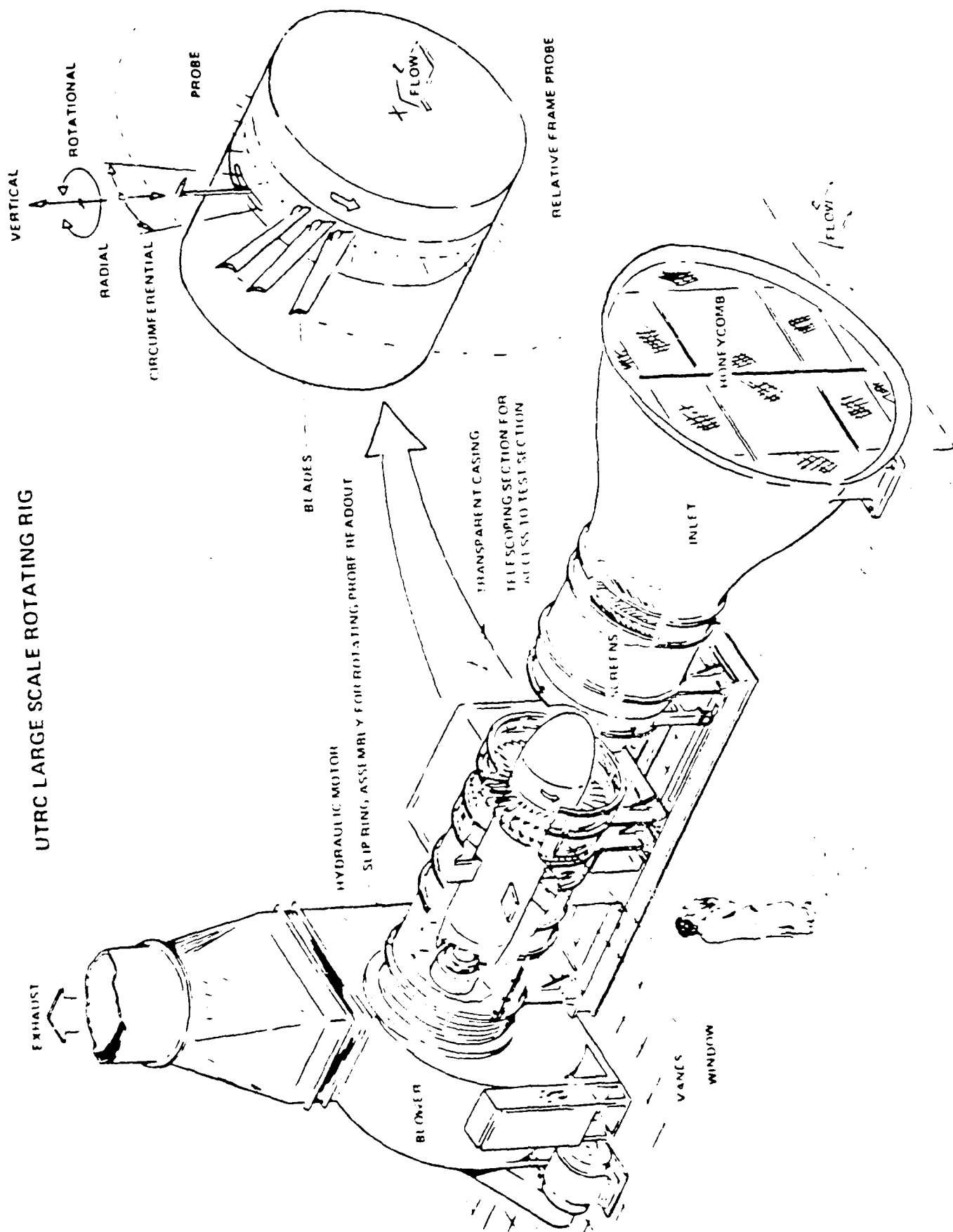III.   EXPLORATORY TESTS USING A ONE-CYCLE DISTORTION SCREEN

Using the general approach outlined in the preceding section, a series of exploratory experiments were made in the Large Scale Rotating Rig, LSRR-I, at the United Technologies Research Center. For these, standard methods were employed for the stationary frame instrumentation. For the instruments on the rotating system however, quite new techniques were developed by Mr. L. W. Hardin, a Ph.D. candidate, who had developed a strong interest and background in solid state electronics. Since the details of the instrumentation design as well as the experimental results of his work are available from Ref. 6, only some highlights and the conclusion are included here.

A drawing of the LSRR-I is shown in Fig. 2. The test section is five feet in diameter and the rotor hub-to-tip ratio is 0.8. The rotor contained 28 blades of chord and span equalling 0.5 feet. Each blade was a eight percent NACA 65-series thichness distribution on a 50-degree circular arc mean camber line. The blade Reynolds number at typical run speeds was 0.5×10^6. The rotor speed and airflow velocity could be controlled independently.

The inlet distortion screen was mounted two chord lengths upstream of the rotor. It was found to give a very satisfactory sinusoidal variation in the axial velocity despite the superposition of a small variation associated with the rig itself. The latter caused some shift in amplitude and phase; the actual measured flow was used in connection with analyzing data from the rotor.

One rotor blade was instrumented with pneumatic pressure taps, pressure transducers and thin film gages, all fairly near mid-span. Six pressure gages were arrayed with a Gaussian distribution on both tne pressure and suction surfaces to impr. ve the accuracy of force and moment determinations ($\pm$ 3%). Data from the thin film gages was not quantitatively analyzed but was inspected for indications of transition to a turbulent boundary layer or flow separation.

FIG. 2

UTRC LARGE SCALE ROTATING RIG

ROTATIONAL

VERTICAL

RADIAL

CIRCUMFERENTIAL

PROBE

RELATIVE FRAME PROBE

FLOW

BLADES

HYDRAULIC MOTOR

SLIP RING ASSEMBLY FOR ROTATING PROBE READOUT

TRANSPARENT CASING

TELESCOPING SECTION FOR ACCESS TO TEST SECTION

HONEYCOMB

INLET

SCREENS

EXHAUST

BLOWER

VANES

WINDOW

FLOW

8

A triaxial hot wire and total head probe was also mounted on a traversing mechanism that was part of the rot.' ; instrumentation. Fig. 3 shows the configuration of the rotating instrumentation.

Considerable experimentation was required to devise a method for handling the many channels of information desired with a limited number of sliprings. Also, the noise problem commonly encountered with sliprings was to be avoided if meaningful high frequency data from the pressure transducers and thin films was to be recovered. The basic idea finally used was to place all the signal conditioning and amplifying equipment necessary to produce high-level signals inside the rotor hub. The system that evolved combined components in a unique way, and was quite effective. Some of the techniques developed have been used extensively on other programs.

In presenting representative results, it is necessary to identify the velocitys and angle nomenclature used by UTRC; the latter are the converse of NACA definitions. Fig. 4 illustrates the geometry. The stagger angle β_1^* at midspan was 30°. Subscript 1 refers to upstream conditions, 2 to downstream. The inlet flow angle, β_1, is defined as

$$\beta_1 = \tan^{-1} \frac{Cx}{\eta}$$

and the exit flow angle, β_2, similarly.

Figure 5 shows the pressure rise coefficient averaged over the annulus for the rotor in both undistorted and distorted flow. The discontinuous curves reflect a hysteresis occuring when β_1 was increased or decreased.

The relation between exit angle β_2 and β_1 as measured by the wedge probe is shown in Fig. 6. Near $\beta_1 = 40\%$ both a momentum calculation and cascade data have comparable values of β_2, but depart significantly for other angles. Three dimensionality in the flow being observed could well account for these disparities, but in the preliminary runs insufficient data at other than midspan was obtained to permit quantitative study.
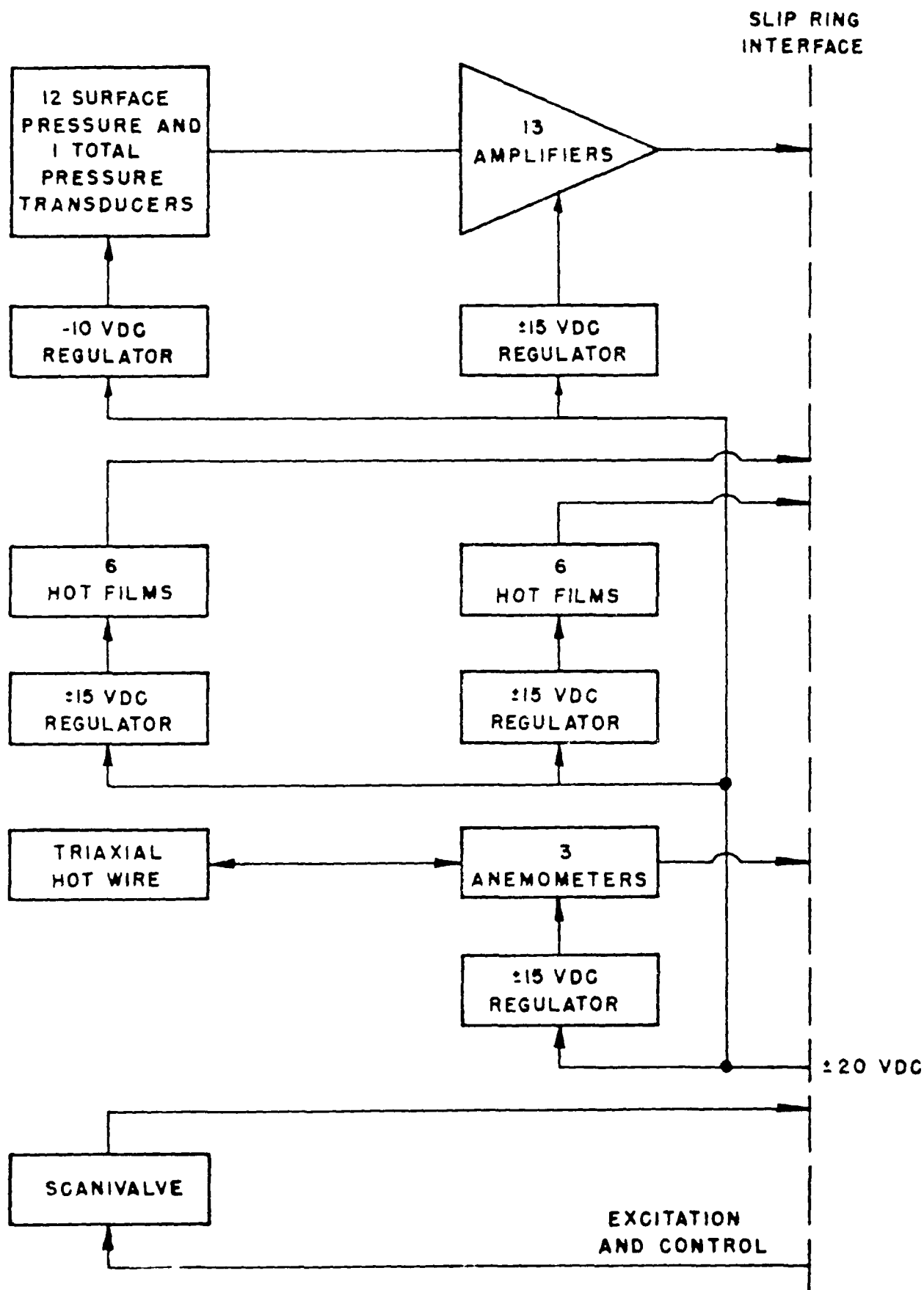
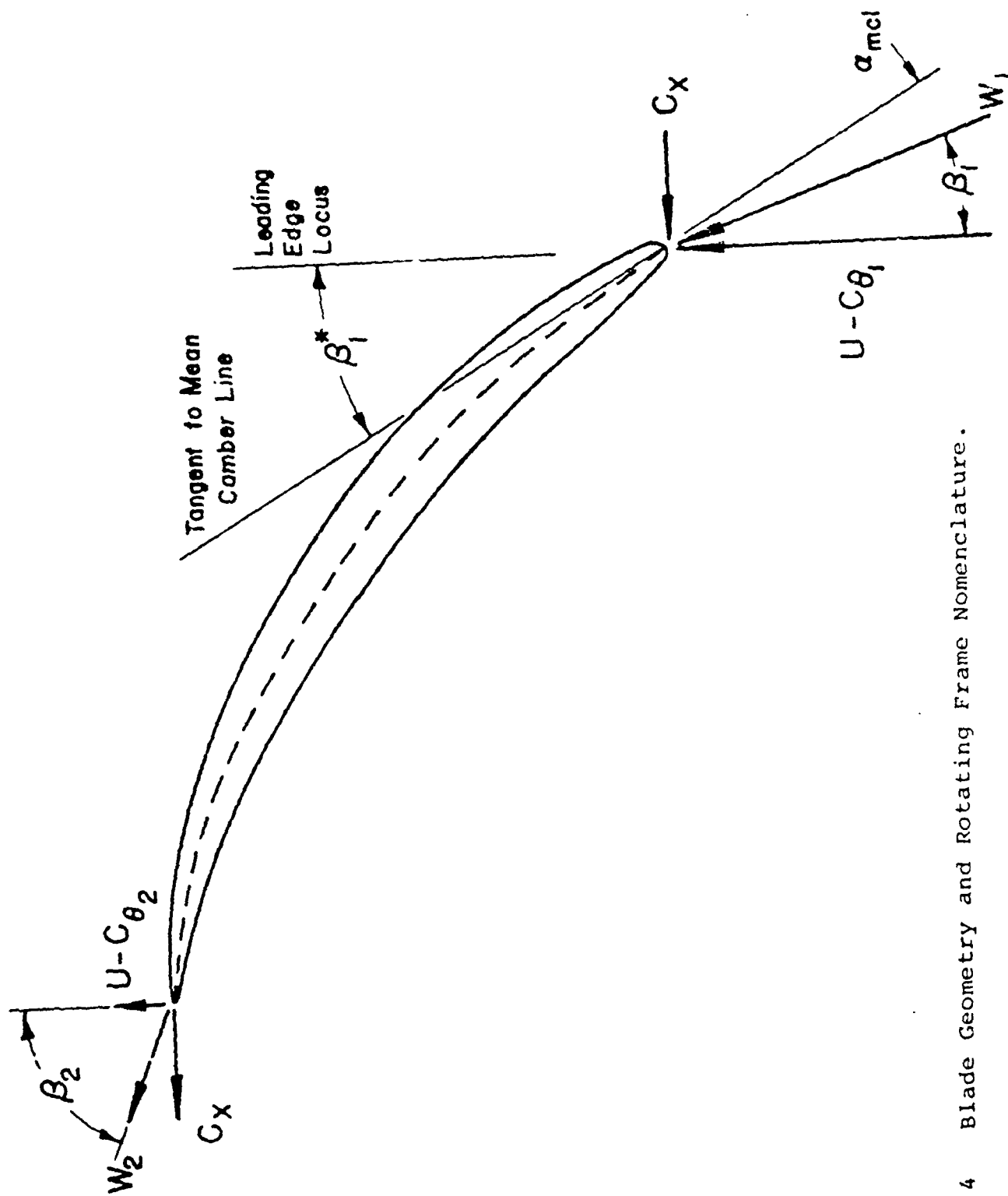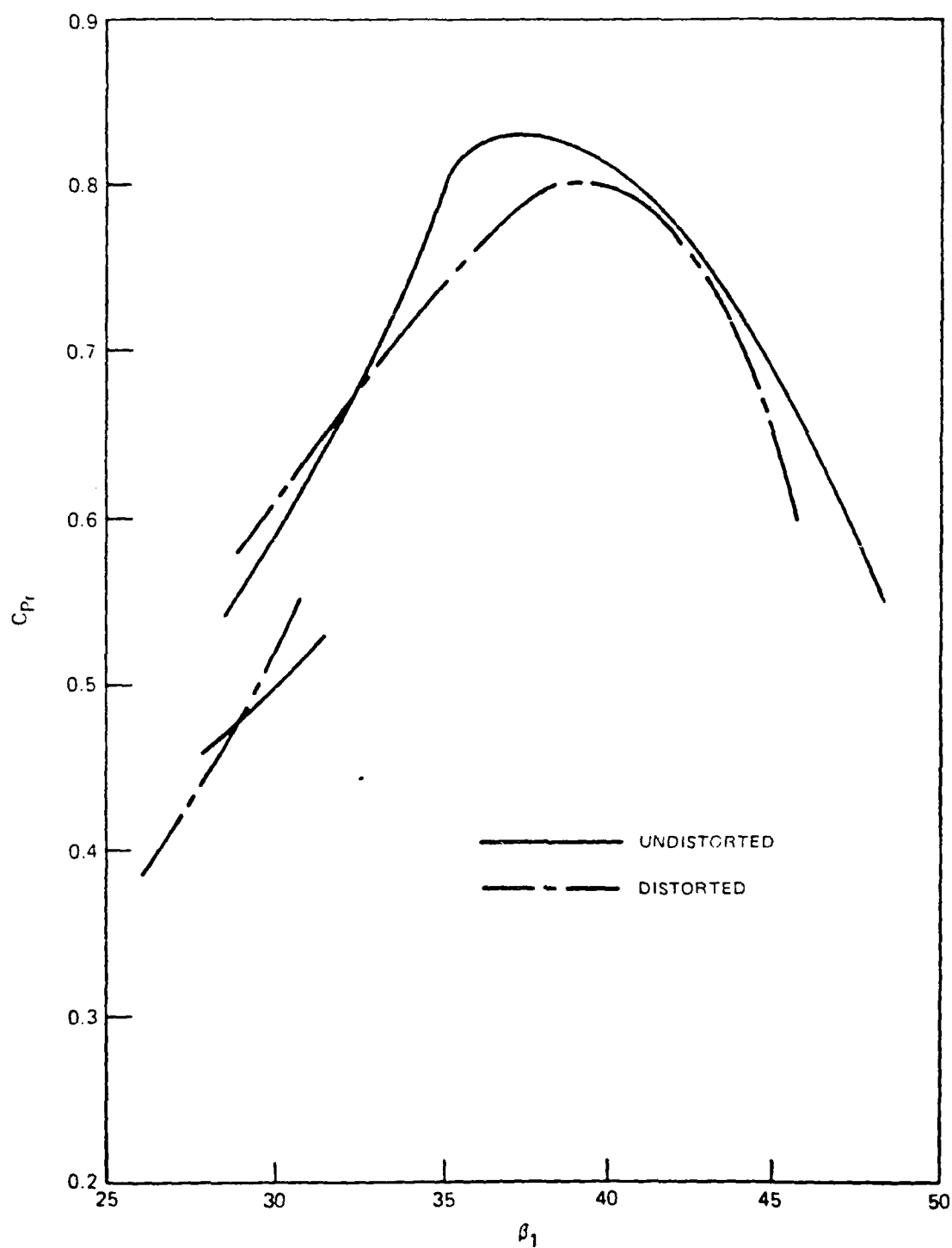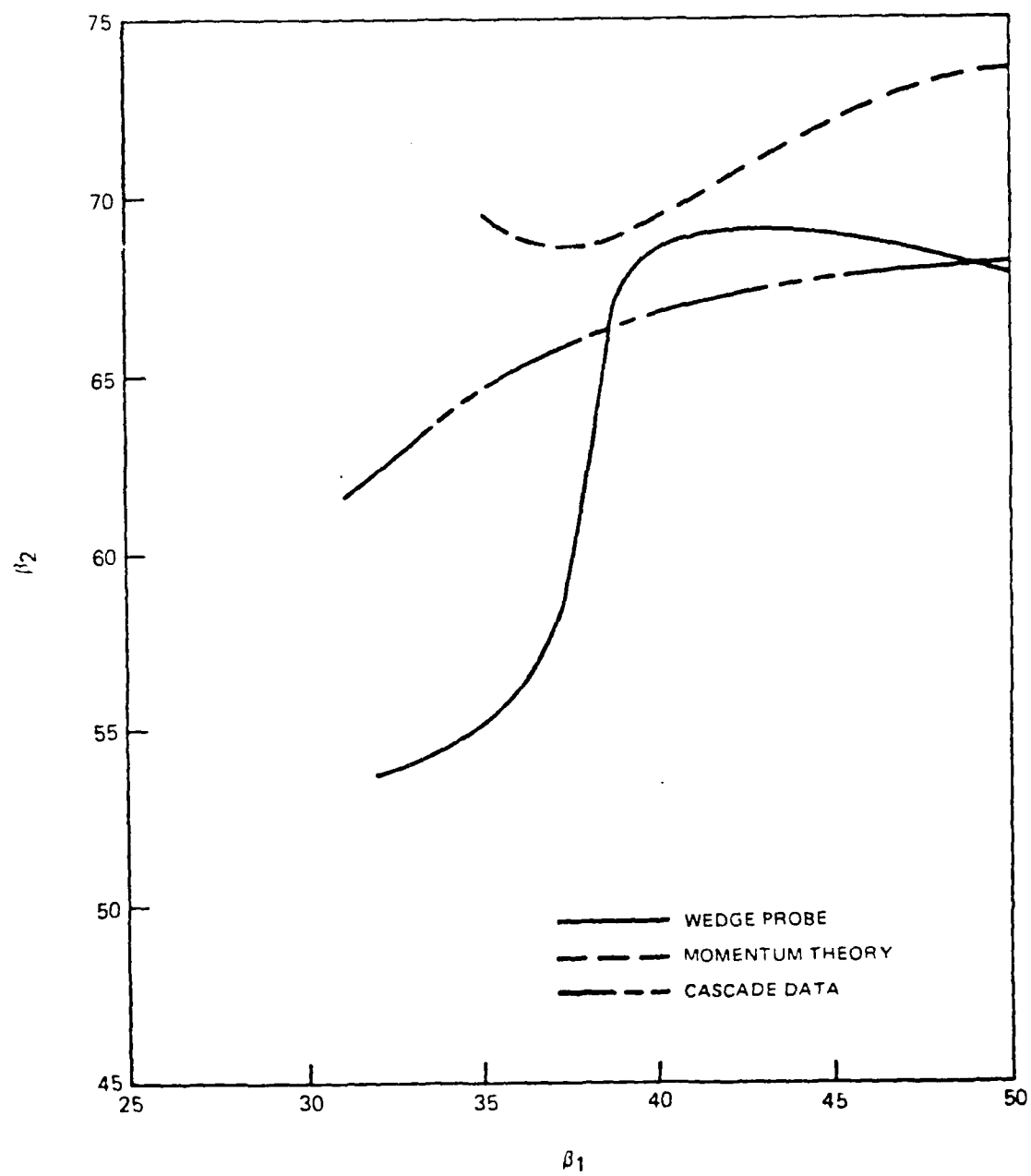Figure 3   Rotating Insrtumentation Configuration.

Figure 4   Blade Geometry and Rotating Frame Nomenclature.

FIG. 5

ROTOR PRESSURE RISE AS A FUNCTION OF INLET ANGLE

FIG. 6

EXIT ANGLE AS A FUNCTION OF INLET ANGLE

Extensive analysis of data at three conditions, $\beta = 29^O$, 37°, and 42° (see Fig. 5) corresponding to light, medium and heavy blade loading was done. Results are also given in Ref. 6 for surface pressures, force and moment coefficients.

The conclussions reached from these runs were as follows:

1. The peak pressure rise on a circumferentially averaged basis is greater for undistorted flow than for distorted flow. However, at low average inlet angle (high blade loading), the rotor produces a slightly higher pressure rise in distorted flow. This is attributed to the fact that the blade transiently operates beyond the steady state stall point at these average inlet angles and yet does not stall.

2. Under high blade loading, the blade pressure distribution exhibits a sharp negative peak on the suction surface near the leading edge. This peaking is more pronounced than in the normal case with an isolated airfoil.

3. As the inlet angle is increased, resulting in reduced blade loading, the pressures on the rear portion of the blade remain essentially unchanged. On the leading edge, however, the pressures undergo considerable change. At the very low blade loadings the pressures on the suction surface of the leading edge are greater than those on the pressure surface resulting in negative loading on the leading edge.

4. As the blade traverses the distortion, the greatest pressure variations occur at the most forward measuring station (x/c = 0.034). The response at this station consistently lags the inlet angle. The response at the second measuring station (x/c = 0.169) is much reduced in amplitude and leads the inlet angle at high blade loading, changing to a lagging response as the blade loading decreases. Pressures at the third and fourth measuring stations (x/c = 0.381 and x/c = 0.619, respectively) show very little

variation for quasi-steady flow. However, under the influence of the unsteadiness created by the inlet distortion, a moderate response is observed. The pressures farther back on the blade essentially follow the quasi-steady characteristic and exhibit very little change with varying inlet angle.

5. The normal force coefficient loops show a significant departure from the quasi-steady characteristic. The amplitude of the response is increased considerably and it generally leads the inlet angle. A significant penetration beyond the steady-state stall point is indicated.

6. The pitching moment coefficient loops are dominated by the pressure response at the leading edge. They show good agreement with the steady state curve at high level angles but depart somewhat from the steady state at low inlet angles.

7. For the lowest average inlet angle which could be attained without the occurrence of rotating stall, a separation bubble is observed to exist on the leading edge of the blade while it is in the low velocity (high loading) region. This may indicate that the inception of rotating stall is triggered by the occurrence dynamic stall in the low velocity region.

8. Velocity and flow angle measurements made at the rotor exit plant at blade midspan indicate that the flow is essentially two-dimensional in the undistorted case. The wake profiles are smooth and relatively constant except for the region immediatly behind the blades where there is a velocity deficit and some flow angle variations. In distorted flow, however, significant radial flow is indicated. This radial velocity component changes direction (from inward to outward) as the distortion is traversed. It thus appears unreasonable to attempt to make quantitative measurements downstream of a rotor undergoing distortion without performing a radial survey of the flow parameters.

9. The circumferential exit angle variations measured in distorted flow appear to be excessive. It is possible that an interaction between the probe and the unsteady flow field behind the rotor is occurring. In any case, a better technique for measuring the flow angle in distorted flow is required.

A nonlinear, large disturbance theory was developed which couples, interactively, the flow through the passages of an isolated, high hub-tip ratio axial compressor blade row and an axially distorted incompressible flow field. The blade row analysis is based on the time-dependent energy equation developed in Ref. 4. The flow field analysis involves the two-dimensional form of the time-dependent, incompressible, viscous Navier Stokes equations. Coupling of the two is accomplished by satisfying the boundary conditions relating the pressure change across the blade row and those requiring mass continuity through the blade row.

As was pointed out in Ref. 2, the analysis requires values of the steady state loss coefficient, X_{SS}, and the flow exit angle, β_2, as functions of entrance turning angle, β_1. In order to make quantitative comparisons between the theory and experiment, it is necessary that X_{SS} and β_2 be determined accurately experimentally. In particular, if spanwise flow exists, as it appears to do in the present tests, combined spanwise-gap averaged values of X_{SS} and β_2 should be used. The experimental tests performed in the present work were designed to give these results for X_{SS} and β_2. When the proposed tests are completed and satisfactory results for β_2 have been obtained, the model will be used to predict the flow property changes across the rotor and direct comparisons to the experimental results will be made and reported upon.

The numerical procedure used to obtain the solution to the finite differenced equations and associated boundary conditions employs the algorithm for solving elliptic problems by direct marching methods given by Roach in Ref. 12. The solution uses a starting procedure which does not require the inlet plane to be far enough upstream to be unaffected by the presence of the blade row. Hence, any experimentally determined distortion at any arbitrary distance upstream of the blade row can be modelled. Details of the analysis are reported in Ref. 7.

The objective of the theoretical modeling for this program has been to investigate the suitability of a flow model for isolated compressor rotors in distorted flows, based on an infinite flat plate cascade operated in steady, subsonic flow. The model would then be compared with experimental data obtained from cascade and LSRR experiments. The first model scrutinized was restricted to incompressible flows only. Reproduction of the author's results were obtained satisfactorily, mainly due to the excellent notation and summarization. The second model investigated was extended to compressible flows. Unfortunately, in this case, duplication of the author's results has proved completely elusive to date.

The model for incompressible flow was first studied, based on a calculation procedure developed by Dr. Dennis Whitehead (Ref. 9). Assumptions made for this model were as follows: 1) the system was restricted to two dimensions; 2) the flow was assumed to be inviscid and incompressible; 3) the cascade blades were considered to be flat plates and were operated at zero mean incidence; 4) the amplitude of vibration was assumed small allowing the problem to be linearized, and 5) all the blades vibrated with the same amplitude and with the same phase angle between them. The imput parameters for this model included spacing/cord ratio, phase angle, stagger angle and frequency. The approach taken was to regard both the blades and their wakes as vortex sheets. The distribution of vorticity along the blade which induced the desired upwash velocities normal to the blade surface was then derived in terms of input parameters and positional variables. Since the force and moment are directly related to the pressure distribution, it was necessary to obtain a relation between the pressure distribution and the vorticity distribution. The resulting integral equation was solved using a transformation which allowed the solution to be approximated by the trapezoidal rule.

It was shown in Ref. 9 that the trapezoidal rule approximation was correct except for a correction needed to account for a logarithmic singularity.

A computer program was then developed based on this model, making use of techniques from matrix algebra to aid in manipulation of equations. The results obtained with this program were identical to those in Ref. 9.

The second model under investigation was developed by S. N. Smith (Ref. 10). The assumptions made for this model were basically the same as from Reference 9 except that the flow was assumed to be compressible (subsonic) and isentropic rather than incompressible. Likewise the imput parameters were identical, with Mach number added. The approach taken in this model was also similar to that in Ref. 9. However, in Ref. 10, Smith made use of the small perturbations to obtain the integral equation in terms of the perturbation quantities, rather than the positional quantities and imput parameters. He then made use of the transformation from Ref. 9 to solve the integral equation by the trapezoidal rule approximation with the logarithmic correction as in Ref. 9.

Another computer program was developed based on this model also using matrix techniques. To aid in the comparison of the two models, equations from Ref. 10 were simplified to the case of Mach number equal to zero, which corresponds to Dr. Whitehead's work on incompressible flows in Ref. 9. In reconstrucing the derivations of equations in Ref. 10 some discrepancies were found, which may, however, be typographical. In an effort to circumvent this problem, both derivations were applied in the computer program with little success. Another obstacle encountered was ambiguous notation, particularly involving the kernal function in the integral equation essential to the solution. After receiving information that Mr. Smith was no longer involved in this field, Dr. Whitehead was consulted concerning these problems. Unfortunately, he was unable to shed any light on the solution.

The current status of the theoretical modeling, therefore, remains stalled for compressible flows, pending further examination of the problems heretofore mentioned. However, the model for incompressible flow is workable and ready for testing against experimental data.

EXPERIMENTS WITH MOVABLE, MULTIPLE-CYCLE SCREENS

Purpose

This experiment in the UTRC Large Scale Rotating Rig (LSRR-II) is a
follow-up on the preliminary experiment in which the performance of an isolated
rotor, in a turbocompressor with an inlet angle distortion, was studied. (Ref. 6)
The same compressor model was used in this experiment in an attempt to quanti-
tatively study the dependence of blade row performance parameters on imposed inlet
angle variations. This will give a foundation for further studies of rotor-stator
interactions. The inlet angle distortion was generated by a sinusoidal variation
in inlet axial velocity created by distortion generating screens. Three different
distortion screens, each with a different number of cycles per revolution, were
utilized. The distortion screens were stepped circumferentially, while fixed
instrumentation at three axial stations measured the distortion pattern. This
system has the advantage of utilizing only a small number of stationary frame
probes since the distortion pattern is moved relative to fixed instrumentation.

Measurements of rotor performance were made in the stationary frame by
inserting probes that surveyed flow properties at five different radial positions.
The surface flow phenomena on one of the rotor blades was to be monitored by skin
friction gages capable of giving improved quantitative results than measured in
the first experiment and the leading edge region of the blade was heavily instru-
mented in order to study critical pressure changes there.

The LSRR-II was operated over three average inlet angle flow conditions with
emphasis given to those angles corresponding to the design point. From this, it
was desired to determine the response of an isolated blade row in terms of exit
angle and unsteady loss to the inlet angle variation.

In a recently completed AFAPL program, Dring (Ref. 11) investigated steady state
flow using the same compressor model. Using some of the same flow conditions that were

used in this program, an attempt was to be made to correlate steady state and unsteady flow variables both on the rotor blade surface and in the rotor wake. The combination of Dring's work and the results of an experiment of this type could be the most comprehensive set of steady and unsteady data on a blade row.

LSRR-II

A new Large Scale Rotating Rig (LSRR-II) has been assembled at UTRC and was used in the present experiment. This new rig is similar to the old LSRR (Ref. 6) but has expanded capabilities which made it more suitable for study of unsteady phenomea than the old rig. Some differences are highlighted below. A more powerful blower is used, resulting in increased axial flow velocities and permitting testing further into the high loss regions of the compressor model than was possible in LSRR-I. A more powerful electric drive motor for the rotor allow rotor speeds up to 1300 RPM, thus providing a far more versatile facility. LSRR-II has a slip ring package with 100 channels, which permits more instrumentation to be placed on board the rotor. The test section components are easily accessible since the entire inlet assemble can be rolled clear of the test section as compared to LSRR-I where the model could only be reached via an axially telescoping section with a limited amount of travel. This advantage also permits a wide variation in axial placement of the distortion screen in future tests, not possible in LSRR-I, and as a result allow a complete decoupling of the rotor blade row from the distortion source. All models used in LSRR-I are completely compatable with that of LSRR-II. In fact, the rotor and blades that were used in a steady state experiment sponsored by the Air Force under Contract No. F33615-77-C-2083 were used in this experiment.

UTRC has a steady state data system that can be used to set the operating point for the LSRR-II model. This data system also reduces on line the steady data to

physical units and records the information on a 9-track digital magnetic tape.
Immediate steady data verification can be made using this system.

All high response data were acquired and recorded on the Aerodynamics
Transient Logging and Analysis System (ATLAS), which accepts up to 26 channels
of high response data. Each channel may be independently amplified and filtered
as required. The heart of the system is a 26-channel transient recorder which
digitizes and stores data in each channel simultaneously at sampling rates up
200 khz as selected by the operator. System control is supplied by an Interdata
7/14 minicomputer system which interfaces with the operator through a graphics
display terminal. The data system is capable of self-calibration using a built-in
programmable voltage standard which is under computer control. Data are recorded
on a 9-track digital magnetic tape for subsequent processing. The system offers
several modes of operation ranging from fully manual, where each step in the
sequence (calibration, acquisition, and recording) is under operator control, to
fully automatic, where these tasks are computer-controlled according to preset
parameters. Since the data are stored on digital tape in a format directly
compatible with UTRC's Univac 1100/81A mainframe computer, overnight processing
is possible. This capability allows immediate detection of any instrumentation
difficulties which may arise and has virtually eliminated the irretrievable loss
of data caused by undetected malfunctions.

The inlet angle distortion in the LSRR-II rig was created by distortion
screens that were designed to give a nominal 20 percent sinusoidal variation in
the inlet axial velocity. One cycle, two cycle, and four cycle distortion screens
were constructed at UTRC. These screens were designed according to the technique
in Ref. 5. A mechanism for moving each screen in the circumferential direction
was designed and built at UTRC. Distortion screens can be moved in fractional
degree increments which are indicated on a digital display while the rig flow
conditions are held constant. The circumferential increments were varied so that
adequate resolution of each distortion pattern was possible.

INSTRUMENTATION

The instrumentation used in this experiment were an improved version of that used in the preliminary experiment. The following improvements were employed. Transient velocity measurements were to be made in the stationary frame at the rotor exit plane, several blade chords downstream of the rotor and immediately upstream of the rotor blade for five different radial positions. Hot film probes were chosen to make these measurements over wedge probes because the initial experimental investigation indicated the existence of severe fluctuations in velocity and flow angles near the rotor exit plane which could not be accurately measured by the wedge probes. The hot film probes can measure the instantaneous velocities and flow angles from which accurate blade gap-averaged values can be calculated. The hot film probe geometry is as follows. At any one axial station, four single slant sensor probes are employed. These probes were placed in the same axial plane but each had a unique yaw angle and was incremented at different circumferential positions. The distortion pattern can be stepped using these same circumferential increments while holding the operating point constant. At any axial station using three carefully selected probes with a range of yaw angles that can best predict the flow angles and by phase-lock-averaging the anemometer output voltage of each probe, the velocity vector can be accurately calculated. This probe design cannot predict high frequency variations but has the advantage of being smaller, resulting in less interference with the flow than a triaxial probe. Furthermore, the reduced size of the sensing volume leads to improved resolution of the wake measurements.

Each probe was calibrated for flow normal to the sensor, flow angle variation, and normal calibration variation with temperature. A method for reducing the data has been developed. The simple reduction scheme used in the initial experiment could not be employed because the probe design does not have mutually orthogonal

sensors. Anemometers for the hot-film probes have been built at NCSU from a design supplied by UTRC.

Unsteady total pressure was measured in the stationary frame at the same radial and axial locations as the hot-film probes. A transducer was chosen that has a minimum amount of thermal drift and is highly responsive to total pressure fluctuations. The sensor housing was designed to minimize the effects of flow angle variations and yet give a high enough frequency response to resolve wake fluxiation in distorted flow. This design employs a small diameter tube (mounted in a Kiel head) which transports the pressure to the transducer at a location out-side of the Kiel head. The advantage of this design is that it is relatively insensitive to large flow angle variations. A study has been made of turning angles in steady state compressor rotor wake data, generated from an experiment by Dring (Ref.11). The results of this study was used to predict yaw angle varia-tions in the stationary frame for distorted flow. The transducers were calibrated for pressure and temperature variation. All electronic instruments required to excite the transducer and condition the signal have been designed at UTRC and constructed at NCSU.

The pressure measuring system located on the rotor blades consists of the same type of instruments used for the previous experiment but a denser array of pressure transducers and skin friction gages were employed near the leading edge of the blade. This was necessary to study the separation bubble which was seen in the first experiment at the leading edge and to accurately map the pressure profile near the leading edge. Transducers were placed only on the suction surface of the blade and no attempt was to be made to compute normal force and pitching moment.

A new type of skin friction gage chosen to give more quantitative results was used on the rotor blade. This gage can make point measurements with little interference from the thermal boundary layer.

The time averaged flow properties were measured in the stationary frame at both upstream and downstream positions. Pneumatic Kiel probes and static taps were used just downstream of the distortion screens, to evaluate the sinusoidal axial velocity pattern. The pneumatic probes used for the steady state measurements were of the same type and had similar locations as in the first experiment (Ref. 6). Measurements obtained from the pneumatic instrumentation was used to set LSRR-II flow conditions while running and as a check on the unsteady measurements.

DISCUSSION OF DATA RESULTS

High response data from probes located at blade midspan were taken for both the undistorted and the distorted cases. Pneumatic data were taken for both test cases. The conditions for which data were taken are listed in Table I.

All pneumatic data taken were determined to be useful in analyzing the distortion pattern and checking LSRR-II parameters. The high response total pressure information was not reduced to physical units but a spot check proved the undistorted part to be in agreement with that of known test data. From a quick inspection of the results, the undistorted hot-film data in the rotor wake region were proven to be erroneous. A more elaborate examination of the data and hot-film probes showed that a problem existed in each probe sensor; namely the sensor relationship with temperature was not holding constant with time. This time varying drift was random and, hence, unpredictable. As a result, it has been impossible to reduce any of the hot-film data. At present, an investigation is underway to determine the cause of the drift and to see if there is any possible way to predict how and why the probes drift with time.

TABLE I

FLOW CONDITIONS FOR NCSU
INLET DISTORTION EXPERIMENT

SCREEN (No. of cycles)	CIRCUMFERENTIAL POINTS	INCREMENT (Degree)	C_X/U (set)	RPM (set)
None	---	---	.60	500
None	---	---	.65	500
None	---	---	.70	500
None	---	---	.75	500
None	---	---	.80	500
None	---	---	.85	500
None	---	---	.90	450
None	---	---	.95	450
None	---	---	1.00	400
None	---	---	1.05	400
1	36	10	.75	500
1	36	10	.85	500
1	36	10	.95	425
2	18	10	.75	500
2	18	10	.85	500
2	18	10	.95	425
4	18	5	.75	500
4	18	5	.85	500
4	18	5	.95	425

The principal investigators at North Carolina State University were

Professor John N. Perkins and Wayland C. Griffith. Dr. Perkins guided the

theoretical modelling effort and supervised the graduate students work.

Dr. Griffith served as project manager for the overall activity, including

the subcontract to United Technologies Research Center. Mr. Frank O. Carta,

supervisor of the aeroelastics group, was principal investigator for the

work at UTRC involving experiments in the LSRRs.

The following students participated in the program while pursuing the

degrees shown.

Larry W. Hardin	Ph.D.
Edward Stinnett	B.S., M.M.E.
Bruce Jackson	B.S.
W. Hugh Hall	M.S.
Linda Lee	M.S.

From the outset the experimental phase of this program had a close and mutually beneficial technical interaction with other projects concerned with transient flows. These include both SQUID- and USAF- sponsored work in the oscillating cascade facility at UTRC, other USAF projects that used the LSRR-I and -II, and to a lesser extent some work on helicopter rotors.

The annual reviews of AFOSR programs on internal flow held at WPAFB provided a valuable forum for exchange of ideas with other investigators during the formative years of this project. Those student participants who were able to attend benefitted particularly from the discussions. The NCSU students who moved to East Hartford to carry out experiments in the LSRR's were able to gain considerable by observing experiments in progress in both the LSRR and the oscillating cascade.

Instrumentation techniques developed under this program, in particular the advances made by L.W. Hardin in on-board conditioning and processing of rotor blade data, have been quite widely adapted and employed on other projects.

The three distortion screens built by Messrs. Hardin and Hall in cooperation with UTRC technicians will, by agreement of the AFOSR and NCSU, be used in subsequent projects. Much of the stationary instrumentation built bv Mr. Hall is being returned to Raleigh for use in teaching in the low speed wind tunnel of the Department of Mechanical and Aerospace Engineering.

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